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Evaluation of a White Seabass (*Atractoscion nobilis*) Enhancement Program in California

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Abstract

The scientific knowledge and technologies needed to attempt marine stock enhancement have grown in recent decades, yet contributions of many enhancement programs to wild stocks generally remain low. Additionally, enhancement programs are often less effective than they could be in contributing to associated social, economic and management objectives due to exclusion of non-science factors in program planning. An independent evaluation of a White Seabass (*Atractoscion nobilis*) enhancement program in California highlighted advances and shortfalls in a 30-year old, publicly funded program. While the program advanced the knowledge of biology and culture of White Seabass, it contributed <1% of fish caught in the state's fisheries. Further, the social and economic impacts of the program remained unassessed despite the potential significance of these impacts. The review highlighted the importance of regular, independent reviews to help stock enhancement programs achieve progress in meeting goals, and for adaptive management. In general, the California White Seabass enhancement program's success in meeting goals was dependent upon the existence of clear, agreed-upon goals and objectives; appropriate levels of funding; internal organizational cooperation; evidence of public benefit and support; improved assessment strategies; and unified, transparent messaging. Lessons learned from this review are applicable to other stock enhancement efforts.

Keywords: finfish aquaculture, fisheries management, hatchery program, integrated management, Sciaenidae, stock enhancement, tag and recapture, White Seabass

1. Introduction

Marine stock enhancement holds promise for augmenting and strengthening resilience of recruitment-limited wild populations that are of recreational and commercial fishing interest. Enhancement effectiveness is not only dependent on the contributions to enhancement itself, which involves the production, release and survival of juveniles in the wild, but also on the contributions of the program to a variety of other biological, ecological, social, economic and management objectives surrounding the environment and the fishery [1–13]. The aquaculture and fisheries science needed to attempt enhancement, in particular the knowledge and technologies needed to breed, rear, tag, release, recapture and estimate the contributions of hatchery fish to wild populations, all exist to varying degrees for different taxa [5, 10]. However, the contributions of most enhancement programs to wild stocks remain variable and generally low [2, 5, 11, 14], indicating that there is much to be learned about applying the science. Further, enhancement programs' effectiveness in contributing to associated social, economic and management objectives tends to fall short due to the trade-offs involved in meeting varied program goals and a general lack of inclusion of these non-science factors in program planning [5, 8, 11, 12].

Commonly missing is the application of a comprehensive (inter-sector) program framework that guides unbiased and well-informed decisions about the most appropriate tools and approaches to use given the place, time, species and other potentially complicated contexts surrounding enhancement [1, 6, 15]. Use of such an integrative framework could help with decisions about the application of science and technology and how best to integrate associated priorities. In particular, the program framework should include factors such as clear, broadly-agreed upon program goals and objectives; integration of stakeholder input and both fisheries and other management priorities; a plan to oversee, evaluate and adaptively manage the program; appropriate funding levels; coordination among program elements and partners, and; information to optimize biological and economic efficiency [5, 10, 11, 15, 16]. A recent evaluation of a marine finfish enhancement program in California highlighted this need to include periodic, comprehensive (inter-sector) reviews of an enhancement program's goals, objectives, and management plan, and provided recommendations for syncing the science with program-wide management [17].

The Ocean Resources Enhancement and Hatchery Program (OREHP) was established by the California State Legislature in 1983 to conduct a program of basic and applied research on the artificial propagation, rearing and stocking of important marine fish species occurring in ocean waters off southern California [18]. The current legislation focuses on determining "if hatchery-released fish can artificially enhance certain stocks of various desirable species, through increased hatchery production of fish and increased monitoring of fisheries to assess the contribution of hatchery-released fish to that enhancement" [18]. The ultimate goal of the OREHP has been "to enhance populations of marine finfish species important to California for their sport and commercial fishing value" [19].

The legislative intent was used to craft a primary goal for the OREHP, which is "to evaluate the economic and ecological feasibility of releasing hatchery-reared fish to restore depleted, native, marine fish populations to a higher, sustainable level" [19, 20]. The original objectives developed to achieve this OREHP primary goal were to:

1. Develop and implement hatchery operation and growout methods that provide a supply of healthy and vigorous fish.
2. Conduct the replenishment program in a manner that will avoid any significant environmental impacts resulting from operation of either the hatchery or pen rearing facilities.
3. Maintain and assess a broodstock management plan that results in progeny being released that have genotypic diversity very similar to that of the wild population.
4. Quantify contributions to the standing stock in definitive terms by tagging fish prior to release and assessing their survival in the field.
5. Continue to develop, evaluate, and refine hatchery operations to maximize the potential for achieving the goal of the program.
6. Develop quantitative measures of success.

The California Department of Fish and Wildlife (CDFW) administers the OREHP with the assistance of the 10-member Ocean Resources Enhancement Advisory Panel (OREAP). The program is primarily funded by revenue from the federal Sport Fish Restoration Act and sales of California Sport Fishing Ocean Enhancement Stamps. The primary hatchery facility where OREHP activities take place is the Leon Raymond Hubbard, Jr. Marine Fish Hatchery in Carlsbad, California run by the Hubbs-SeaWorld Research Institute (HSWRI), the OREHP's primary contractor. As part of their OREHP contractual obligations, the primary contractor has developed the culture protocols required to raise White Seabass (*Atractoscion nobilis*) [17, 20] and has conducted research on culture protocols for other species, including California Halibut (*Paralichthys californicus*), California Yellowtail (*Seriola lalandi*), Giant Seabass (*Stereolepis gigas*) and California Sheephead (*Semicossyphus pulcher*) (see [21, 22]).

The OREHP is the longest-running experimental marine fish stock enhancement program in the United States, created in 1983. There were no formal assessments of the program until early 2015 when California Sea Grant (CASG), at the request of CDFW, began to coordinate a comprehensive review of the OREHP, including its progress in achieving its goals and objectives. With guidance from CDFW, CASG created a nine-member Science Advisory Committee (SAC), comprised of scientists from around the country, and tasked them with evaluating the program. The SAC, appointed by the CDFW Director, included members with demonstrated expertise in a wide variety of disciplines, including aquaculture, fish pathology, population dynamics, genetics, and water quality. Comprehensive and rigorous evaluations of marine enhancement programs are, in general, lacking, making this thorough and detailed evaluation one of the first of its kind.

2. Evaluation of the program

The SAC spent 2 years (2015–2017) conducting a review of the OREHP hatchery and enhancement operations. The purpose of the review was to assess the program's functionality and efficiency, environmental impacts, scientific accomplishments, economic costs and benefits,

and contribution to the wild White Seabass stocks [17]. The SAC reviewers also considered alternative hatchery uses.

2.1. Fulfillment of the ultimate program goal: enhancement of marine fish stocks

The review concluded that the OREHP met the intent of the program laid out by the California State Legislature to conduct basic and applied research on the propagation, rearing, stocking, and distribution of an important marine fish, White Seabass [18]. In 1983, little was known about the techniques needed to successfully spawn, rear, and release saltwater fishes [9]. Since then, the OREHP has significantly contributed to the world's knowledge about marine enhancement science and techniques (see Chapter 6.3 in [17]). However, the review also found that White Seabass enhancement had not been effective to date, and thereby the program had not fulfilled its ultimate goal.

An analysis conducted for the review [17] using tag-recapture data generated by the OREHP between 2000 and 2011 [23] indicated that the program made a less than 1% contribution to the California White Seabass fishery due to high levels of mortality suffered by hatchery-reared White Seabass following release into the wild. According to the analysis, if mortality rates of released hatchery fish were reduced to equal those of wild White Seabass, then current stocking rates could result in a hatchery contribution of 18% instead of <1% of the total fishery catch [17]. Therefore, in order to achieve fisheries enhancement, the approaches and technologies developed for White Seabass would require further development aimed at reducing post-release mortality, including the related recommendations made throughout the evaluation report.

It should also be noted that, whereas the White Seabass stock was considered to be depleted when the OREHP was initiated and White Seabass was chosen as the program's focal species, the stock has since increased, likely due to a combination of high recruitment related to favorable environmental conditions and fisheries management measures (e.g., closure of the coastal gill net fishery) [24], and then decreased again, likely due in part to unfavorable environmental conditions [25].

2.2. Fulfillment of the six OREHP objectives

The review [17] concluded that several of the six OREHP objectives had been partially or fully met. The biggest achievements of the OREHP have been its contributions to research discoveries surrounding the biology and culture of all life stages of White Seabass (Objective 6) and the transferability of those discoveries to other marine finfish species. Other notable successes include the development of appropriate hatchery (Objective 1) and tagging methods (Objective 4) for White Seabass, and the constant improvements in hatchery practices that have been made over the years (Objectives 1 and 5). Through its program of releases of tagged fish, and fisheries-independent and dependent monitoring of released fish, the OREHP had successfully collected enough data to evaluate the post-release survival of hatchery fish and the contribution of hatchery fish to the White Seabass fishery (Objective 4), both of which were determined to be low. Substantial engagement and outreach regarding White Seabass life history and culture has been conducted to the sportfishing community, K-12 students, and members of the

interested public (Objectives 1 and 6). Further, there has been no evidence that the program has caused any adverse environmental impacts at the production levels to date (Objective 2).

Other OREHP objectives, or aspects of objectives, were deemed to be unmet. The analysis of tag-recapture data revealed that hatchery fish suffer high mortality rates within the first few months following release (Objective 1) that likely limit contributions to fishery stock. Low post-release survival and fishery contribution rates likely stem from some combination of fish health and fitness challenges (e.g., effects of unresolved gas supersaturation issues, inconsistency in diagnosis and response to health findings, domestication effects; Objectives 1 and 4), and uncertainty about optimal release strategies (Objectives 1 and 4). While the maintenance of genotypic diversity (Objective 3) has not been sufficiently addressed throughout the program, the lack of significant hatchery contribution to the wild population has prevented any adverse genetic effects to the wild population (e.g., the Ryman-Laikre effect) [26, 27].

2.3. Budget conclusions

The review revealed that the operating budget needed to achieve all aspects of the OREHP objectives exceeded the base funding level of approximately \$1.6 million per year that had been available for the program. With inadequate funding, the OREHP objectives suffered. Restricted funding reduced or limited several OREHP capabilities, including the ability to exchange broodstock at rates needed to ensure adequate genetic diversity in released fish (Objectives 1 and 3), provide stricter oversight of volunteer-run growout facilities (Objective 1), address reoccurring gas supersaturation issues (Objective 1), consistently and extensively perform and address challenges related to recapture surveys (Objective 4), and perform fisheries enhancement modeling (Objective 4). Limited resources also likely prevented the initiation of a genetic monitoring program (Objective 3) and (socio-) economic assessments (Objective 5 and 6). The primary OREHP contractor contributed in excess of \$400,000 annually to meet operational expenses that were at least in part related to the OREHP, and sought grants and both monetary and in-kind contributions from a mix of private and government sources to make infrastructure repairs and improvements to the hatchery facility, to get assistance with White Seabass collections, and to operate the volunteer-run growout facilities [28]; the contractor also brought in external funds to cover research and outreach efforts that were related to, but not part of, the OREHP.

2.4. Lessons from the program evaluation

While the scientific and aquaculture advancements of the enhancement program have had worldwide impacts, the negligible (<1%) contributions of hatchery fish to fishery stocks revealed that there is still much to learn about applying the science, given the conditions and uncertainties under which the program operates (e.g., inadequate funding, uncertainty about the causes of post-release mortality and the drivers of White Seabass population change). Insufficient funds to support the dual objectives of research and actual enhancement, as well as a lack of consensus about which of the two objectives was the higher priority, likely contributed to the shortfalls in meeting program objectives. Decisions about research priorities, integration of aspects of the program with other social and fisheries

management priorities, and funding requirements and levels need to be made in a comprehensive, program-wide, coordinated fashion.

3. Program level recommendations

Although the review [17] did not include a comprehensive review of OREHP management processes, it recommended that the organizational structure of those groups overseeing the OREHP be updated to better achieve program goals and objectives. The review also highlighted several program-level weaknesses and made recommendations for strengthening the OREHP.

3.1. Need to strengthen and update the program organizational structure

The ultimate authority for many programmatic decisions within the OREHP was unclear. It was deemed necessary to clarify, for example, who had the authority to make decisions relating to research priorities and issues that influence hatchery operations and scientific research, or issues that put these two things into conflict with one another. Part of this uncertainty was caused by the OREHP's dual focus on production and research, two activities which can be very different and for which there were limited resources. Additional uncertainty may have been due to "mission creep" — the change in the internal interpretation and communication of OREHP intent, goals and objectives through time, and in the absence of periodic program reviews.

The review [17] noted that the program's advisory panel (OREAP) had not been as effective or valuable as it could have been, and that CDFW should reconsider how to best utilize an advisory panel. The current OREAP does not include representatives from all of the groups detailed in the original legislation, as some of these groups no longer exist or have changed focus. It was recommended that CDFW restructure and reconstitute the OREAP, and, in addition, create an independent science and technical advisory group with expertise in hatchery science (and associated issues, such as fish health), population dynamics, release and recapture strategy optimization, and genetics to help develop and evaluate quantitative criteria, benchmarks, and timelines to be used in future, regular evaluations of the program.

3.2. Need for external, independent guidance

3.2.1. *Fish health guidance*

The OREHP voluntarily has one of the most rigorous fish malformation, or deformity, assessment protocols of any of the stocking and supplementation programs in the U.S. (see Chapter 1.9.1 in [17]). The deformity level of hatchery-raised White Seabass, as with many other cultured fish, is generally of little concern because the deformities are typically thought to be linked to environmental factors, such as nutrition, water temperature and water quality, and therefore pose little risk to wild fish [17, 29–31]. Deformities in yet other cultured fish have, however, been shown to have low to sometimes moderate heritability [32–35]; because the OREHP is charged with research, the monitoring of physical anomalies informs the program's scientific research (see Chapter 1.9.1 in [17]) and provides a better general understanding of the underlying causes and effects of deformities.

The main concern about deformity that emerged during the review was the difference in opinions between the pathologists working for CDFW and those working for the primary contractor regarding the definition of deformed fish, and the implications of the range of morphological variability found in hatchery fish for vigor and fitness. These differences in opinion catalyzed a large public relations problem and inhibited smooth operations at the Carlsbad hatchery, thereby resulting in reduced juvenile production due to diversion of resources and delays in decisions about health diagnoses and appropriate responses. Further, differences in opinion, and therefore the outcome of diagnoses and actions taken, may have ultimately affected release numbers and post-release survival. Although risk of introduction of disease or unwanted genetic characteristics to the wild fish population via deformed fish is low due to the low likelihood that deformities are linked with disease or genetics, it is critical to have consistent decision-making criteria and to set appropriate policy for dealing with malformed fish so the OREHP can meet its objective of producing healthy and vigorous fish. The review strongly recommended that CDFW and the primary contractor engage an independent panel of experts that would be charged with the following:

1. Compare the morphological diversity of wild fish with that of hatchery fish.
2. Determine which unique hatchery morphologies pose a genetic or other biological threat to wild populations.
3. Determine which morphologies cause a measurable loss in post-release fitness.
4. Develop a set of criteria and protocols for identifying and responding to fish that have unacceptable phenotypes and/or levels of deformity that both CDFW and the primary contractor's staff agree upon.
5. Develop approaches that minimize frequencies and levels of deformities.

3.2.2. Science and technical advice

The review [17] strongly recommended that CDFW periodically enlist an independent external group of science and technical experts to work with CDFW and stakeholders to develop, and later to help evaluate, a set of quantitative criteria, benchmarks, and timelines for each of the established OREHP objectives. The review presented assessment topics within each OREHP objective that guided determinations about the extent to which each objective had successfully been met. However, needed is the further development of a set of more focused, clear, feasible, and occasionally updated metrics (e.g., see Chapter 6 in [17]) that would allow for more efficient, and more frequent, assessments of the program, and that would provide clearer guidance to OREHP staff and researchers.

3.3. Need to strengthen public communication and transparency

Throughout the program's life, the primary contractor has taken the lead on public outreach, stakeholder engagement, and public relations for the OREHP without provision of communications and development professionals, or adequate resources to support this task. This responsibility taxed the contractor's already limited resources for the OREHP and added the stress of

public scrutiny. The reviewers occasionally had to dig deeply to find information needed to assess the status of various aspects of the OREHP and noticed the presence of potentially confusing statistics about various aspects of the program in reports and non-peer reviewed publications (e.g., newsletters). The review recommended that the primary contractor and CDFW make greater efforts to keep information about the OREHP openly available to each other and to the public, and to improve consistency and transparency of outcomes and incidences, particularly for issues of public interest (e.g., contribution of the program to wild stocks, recapture rates of tagged fish in gill nets, incidences of disease and deformity, occasional accidents or die-offs, costs and benefits of the program, etc.). Improved transparency may include the development of a process that allows communication with a broad range of stakeholders, including those not already associated with the program, to collect input regarding priorities and development of the program. Further, the review recommended that CDFW assist more with this duty, or find and support knowledgeable public communications professionals to help.

4. The future of the program: review and reform

The evaluation of the OREHP objectives, goals, intent and budget indicated that 30 years was too long for the relevant authorities and stakeholders to wait to review and reevaluate the overall focus and strategy of the program. The evaluation showed that, while the research and technology development objectives of the program have largely been met, the program is not currently in a position to substantially enhance the White Seabass fishery due to a variety of factors, including high post-release mortality of juvenile White Seabass. Further, the California White Seabass stock, which is estimated to have been very low when the OREHP was established and White Seabass was chosen as its focal species, has cycled through a higher level of abundance and is again in decline [25]. Additionally, White Seabass proved to be a difficult species to use in enhancement, in part due to its lack of site fidelity and long, oceanic dispersal distances and distributions outside of U.S. waters. These factors, together with changes in the status and management of other California stocks, and increased understanding of the potentials and limitations of stock enhancement to contribute to fisheries management outcomes (e.g., see [11, 15]), suggested that it is timely to reassess the program's utility, and to review and reform the program's priorities and the approaches used to fulfill each of the program's objectives.

The review [17] outlined the following five steps (4.1–4.5) for assessing the future of the OREHP (**Figure 1**), noting that these recommendations were made without consideration of cost and thus would need to be evaluated with respect to program priorities and levels of available funding.

4.1. Step 1: conduct a science-based and participatory public process

The OREHP review indicated that the future of the program should be determined through a process that is both science-based and participatory with respect to the program's stakeholders (**Figure 1**) (e.g., see [4]). Overall guidance for such a process can be found in the Updated

OREHP Action and Decision Tree

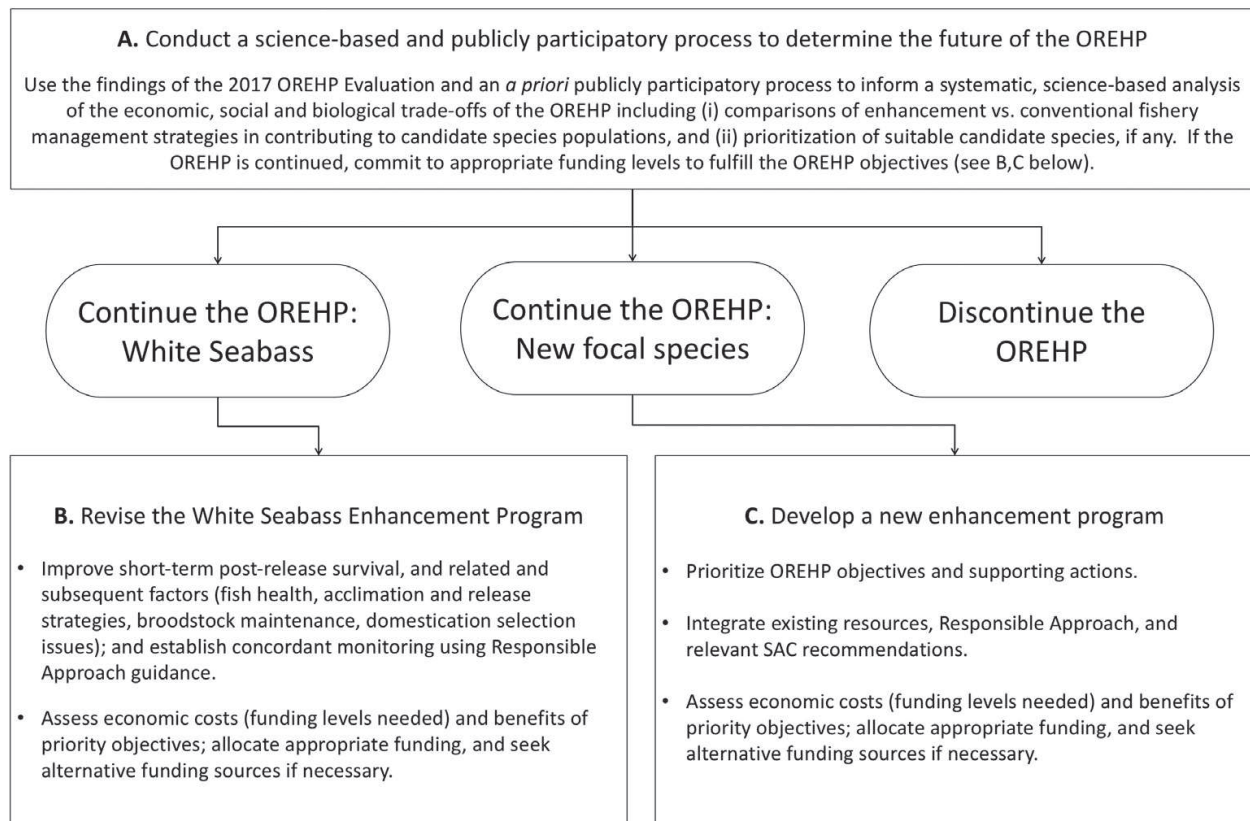


Figure 1. Flow chart of decisions and actions resulting from the Ocean Resources Enhancement and Hatchery Program (OREHP) evaluation.

Responsible Approach to Marine Fisheries Enhancement [6] and in the Hatchery Reform processes implemented for several salmon hatchery programs in the Pacific Northwest [36]. Scientific methods, such as fisheries models used to assess the potential effectiveness of stock enhancement and other fisheries management measures in achieving desired fisheries management outcomes, enable a systematic approach to the planning of enhancement programs. Stakeholders, principally recreational and commercial fishermen, have played a major role in the operation and funding (through license fees) of the OREHP. The program review suggested that it is therefore imperative to involve stakeholders systematically and constructively, and to use current scientific information in making the following decisions about the program's future direction [17].

4.2. Step 2: assess the potential role of enhancement in California fisheries management

The OREHP review indicated that the list of candidate species, including White Seabass, that was identified by CDFW and the primary contractor for use during the review should be honed using analysis of the biological, economic and social costs and benefits of utilizing an

enhancement program as compared to relying solely on (non-OREHP) fishery management strategies (e.g., updating catch quotas and/or size limits) to conserve and manage each of the species (**Figure 1A**). If the analysis indicates that conventional fishery management strategies alone may be sufficient for the conservation and management of most candidate species, then discontinuation of the program should be considered as one option, if legislatively feasible. If some stocks are deemed to be extremely low (i.e., severely depleted), and/or if responses to conventional fishery management actions alone are predicted to be ineffective, then further development or modification of the enhancement program should be considered, and funding adjusted to enable the program to meet its objectives. The candidate species list put forward by CDFW and the primary contractor was generally supported by the review committee, with California Halibut of particular interest for inclusion in this initial assessment given the available information on its biology, ecology, and culture practices, its depressed populations [37], and the high recreational and commercial fishing demand.

4.3. Step 3: prioritize candidate focal species by enhancement potential

The OREHP review recommended that if the initial assessment of the value of enhancement in relation to other fishery management strategies indicates that the program could likely contribute to some of the candidate species' stocks, then those species remaining on the candidate list should be prioritized. Specifically, an *a priori* systematic and quantitative assessment of each candidate species (**Figure 1A**) (e.g., see [13, 38]) should be conducted in cooperation with an independent advisory committee and should include input from a broad range of stakeholders, consideration of economic and social costs and benefits, and more consideration of fit with fisheries management strategies (e.g., see [11]). Criteria should include depressed stock numbers (e.g., consistently low enough to offset genetic risks associated with enhancement), ease of culture, life history that is amendable to rearing, tracking and enhancement (e.g., relatively high growth rates, not highly dispersive), geographic range that can be feasibly sampled (e.g., most common in U.S. waters), availability of existing biological information, and high demand and value within commercial and recreational fishing industries and throughout the food supply chain (see Chapter 6.5.3 in [17]). Clearly, the findings of the economic, social and ecological (e.g., environmental, genetic and population-level) trade-offs analyses used to narrow the candidate species list may be used to inform this process.

The challenges associated with each candidate species should be assessed and applicable recommendations from the OREHP evaluation report [17] should be used. For example, a fish with a range that extends into Mexico will require collaborative efforts for population/fishery assessments, and relatively slow growth rates will still require decisions surrounding size at release trade-offs. New challenges should also be assessed; for example, the demersal California Halibut would require different tank designs than those established for the pelagic White Seabass, and as such would require a significant capital contribution to reconfigure hatchery systems.

If a change of focal species is decided, White Seabass should be phased out by ceasing breeding efforts while completing the rearing and release of existing early life stages. The rate of phasing, however, may depend upon space, resources (including availability of new species

broodstock), and other logistical considerations. An independent advisory panel should be used for guidance on planning of the phasing and the development and initiation of a new enhancement program (**Figure 1C**).

4.4. Step 4: focus future White Seabass enhancement on reducing post-release mortality

The results of the program evaluation stress the importance of minimizing post-release mortality of hatchery White Seabass to increase the potential of the enhancement program. The same need would likely exist for new focal species that might be chosen for enhancement. Greater emphasis should therefore be placed within the program on research of factors that affect post-release mortality, and on husbandry and release strategies that minimize this mortality (**Figure 1B**) (e.g., see [39–42]). This focus may require increased funding to the program in order to fulfill a commitment to understanding, and subsequently reducing short-term (e.g., 6 month) post-release mortality rates. Increasing production to compensate for high mortality rates is not recommended because of the increased expenses, increased infrastructural and resource needs (e.g., staff time, supplies), and increased risk of fish health issues that would be associated with higher production rates.

In particular, to improve survival and stock contribution rates, greater attention should be given to:

1. Domestication issues (Objective 1).
2. Resolution of fish health challenges (e.g., resolving gas supersaturation and its health effects, understanding effects of deformity types and severity on fitness, consistency in diagnosis and response to health findings; Objective 1).
3. Continued improvements to placement and oversight of growout facilities (Objective 1).
4. More research focused on optimizing release strategies such as timing, size, location and magnitude of releases (Objectives 1 and 4).
5. More effort on post-release monitoring needed to optimize release strategies and estimate recapture rates (Objective 4).
6. Greater integration with fishery management to understand relationships between enhancement efforts and wild populations/fisheries (Objective 4).

If White Seabass production is increased or if there is a change in focal species, however, potential environmental impacts associated with these changes should be reassessed (Objective 2), and monitoring efforts should be modified appropriately to account for higher production levels and/or different impacts depending upon system changes (all Objectives).

If survival rates increase, improved genetic practices and monitoring should also be implemented in order to address the potential genetic effects associated with enhancement (e.g., the Ryman-Laikre effect [26, 27]), which to date have not been an issue because of the extremely

small possibility that a hatchery fish will survive to spawn with wild fish. If higher survival rates become the focus, then the broodstock management plan should be reassessed and reworked to include more frequent rotation of wild-caught broodstock, more emphasis should be placed on reducing domestication selection and increasing the proportion of spawns that go on to be reared, and monitoring of family contributions throughout the rearing process should take place to maintain the desired levels of genetic diversity and limit domestication selection (Objectives 1 and 3).

Further, a framework for conducting, evaluating and refining the enhancement program (Objectives 5 and 6) should be developed and used, regardless of the focal species selected. For example, the Updated Responsible Approach to Marine Stock Enhancement proposed by Lorenzen et al. [6] provides guidance on goal setting and evaluation, research and technology development, and adaptive management strategies (Objectives 5 and 6). In particular, an economic analysis should be performed for whichever program approaches are selected in order to ensure that the financial benefits of the program outweigh potential costs, and to inform future assessments (Objectives 5 and 6). More attention should also be given to adaptive management [1, 6]. The OREHP has many hatchery and growout protocols and plans in place, but data collection, record keeping, and reporting are not currently structured to allow formal assessment of whether protocols are being followed, and how findings and operational changes are contributing to protocol updates. For example, release strategies need to be optimized, and more formal data collections, record keeping and reporting of results (i.e., adaptive management experiments) can inform the evaluation of model assumptions about survival and the effects of fish size at release, release (micro)habitat, season, acclimation and acclimatization, and release magnitude. An adaptive management approach would also be useful for addressing many of the other challenges identified through the review.

4.5. Step 5: address the economics of the enhancement program

4.5.1. Assess the economic benefit of the program

The OREHP review indicated that, given that funds for the program are largely public and much of the benefit of the program may be social, a socio-economic analysis would make program expenditures more defensible, help to indicate social and economic strengths and weaknesses of the program, and may provide insights into stakeholder priorities (e.g., see [12]). Improved economic awareness and efficiency is important because the accomplishment of priority objectives, and the breadth and depth of actions needed to fulfill those objectives, will be dependent upon available funds (**Figure 1B, C**). The extent that review recommendations can be implemented will also be dependent upon funding levels. For example, if the program's funding remains static, it may be necessary to narrow the focus of the program to solving the challenges of enhancement that were identified to be the highest priority in the review (e.g., reducing post-release mortality). But, if funding is increased, then there may be opportunity to also test and address the challenges of a program that contributes more significantly to wild populations (e.g., developing and initiating genetic monitoring). However, resolution of all identified challenges exceeds the scope of a relatively small increase in funding and may require alternative funding sources, such as private organizations or foundations.

4.5.2. *Need to expand public-private partnerships*

There is a need to expand public-private partnerships such as those established already within the program. The primary contractor for the program has forged partnerships with private groups, such as recreational fishing groups and private foundations, which have provided a substantial supplement of non-program funds and in-kind resources (e.g., volunteer time, boat time, supplies) to operate the hatchery and growout facilities. Because of the infusion of supplemental funding from the primary contractor, the review considered the potential for conflict of interest, and concluded that the State has benefited from the private funding, and that all information has been publically shared so that there is no conflict of interest among partners associated with the program. If the program continues, CDFW should consider expanding the public-private partnership concept to bring in additional partners (and funds), such as other foundations and commercial fishing communities, to expand the capabilities of the program, which may allow for the implementation of recommendations made in the review for fulfilling each program objective.

5. Roadmap to enhancement based on lessons learned

Enhancement programs, such as the OREHP, often contribute to knowledge about the biology and culture of marine species [5, 10]. Actual stock enhancement, however, tends to be low, as does effectiveness in contributing to associated social, economic and management objectives [2, 5, 8, 11, 12, 14]. The shortfalls of enhancement programs are often due to the dynamic nature of marine environments and also to the need to meet the varied, sometimes conflicting, objectives of a program that include social, economic and management goals [5, 8, 11, 12]. This is especially true for programs lacking sufficient funding to accomplish multiple objectives or regular program assessments.

New enhancement ventures or those that have been underperforming in one or more ways would do well to perform a systematic analysis of the economic, social and biological trade-offs of their programs. Involvement of public input in this process is recommended to ensure stakeholder needs and values are addressed because fisheries are characterized by complicated biological, social and economic interactions [5, 6, 8, 11, 12]. First, a list of candidate species should be identified based on need (e.g., depressed population sizes), availability of scientific information for the species, conduciveness to enhancement (e.g., ease of culture and monitoring, drivers of initial decline addressed, if possible), low risk of harm to wild populations if post-release survival is high (e.g., low risk of inbreeding depression and density dependent mortality), and stakeholder desirability [13, 38]. To hone and prioritize this species list, biological, economic and social costs and benefits of enhancement should be assessed, to the extent possible, for each species. These assessments should include comparisons of predicted outcomes of enhancement with those of conventional fishery management strategies alone (i.e., no enhancement); if there is high expected benefit from enhancement relative to other fishery management actions, or if benefits are predicted to outweigh costs, species should be made a higher priority.

Planning for the enhancement of a chosen focal species should start by defining clear, broadly supported goals that consider the whole fisheries management system, and a prioritized set of objectives with supporting actions to achieve the goals [6, 17]. Use of pilot studies, especially when focusing on species not previously used in enhancement efforts, is highly recommended for improving understanding of the information, technology and approaches needed for developing practices and plans, as well as for testing the feasibility of culture, release and recapture [6]. Establishment and use of an independent, cross-sector advisory panel with expertise in relevant scientific fields, fisheries management, economics and stakeholder engagement, as well as an accountable decision-making process are advised [17]. Adaptive management and regular program-wide reviews should form the scaffolding of both short-term (day to day-within year) and longer-term (inter-annual-5-year periods) decision-making processes. As challenges arise, such as fish health problems or high post-release mortality rates (causing low recapture rates, for example, see [17]), resources may be re-allocated in real time to address challenges, or research and production objectives refocused on more feasible priorities given levels of funding or conditions. Assessments of economic costs and benefits of priority objectives should guide allocation of appropriate funding levels along the way, with effort dedicated to alternative funding sources, if necessary [17].

Once implemented, the breadth and depth of enhancement efforts, and, ultimately, the progress in meeting program goals, will be dependent upon the existence of clear, broadly agreed-upon goals; appropriate and sustained levels of funding; internal organizational cooperation and support; evidence of broader public benefit and support; rigorous and accountable assessment strategies, including strong adaptive management and frequent assessments using well-defined ecological and economic metrics; and unified, transparent public communications in order to clearly demonstrate the values of the program to commercial and recreational fisheries and society.

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The authors have no non-financial, financial or material conflicts of interest that could have influenced this scientific work.

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